



Aquatic effects of peat extraction and peatland forest drainage: a comparative sediment study of two adjacent lakes in Central Finland

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Abstract The aquatic effects of forestry practices and peat extraction continue to cause serious concerns. The effect mechanisms of peat extraction on water quality and aquatic ecology of the receiving surface waters are well known, but the impacts are often difficult to differentiate from those of forest management. A pairwise temporal sediment study was conducted on two adjacent lakes in Central Finland to study whether the unique effects of peat extraction can be detected in an area of intensive forest drainage. Both lakes are affected by forestry, but the reference lake has no history of peat extraction in its watershed. The deepest parts of the lakes were cored through the lacustrine sediments, and the recent carbon and dry matter sedimentation rates were compared to their site-specific reference values. Recent changes in benthic macroinvertebrates (chironomids) and diatom algae were studied to assess the ecological effects of these practices in the lakes. No significant differences in recent increases in carbon accumulation were found between the peat extraction-impacted lake and the reference lake. The pairwise comparison allowed identification of a regional pattern of impacts that is closely related to the history of land use, particularly forestry, in the region. The approach also allowed identification of the transient signs of peat extraction in the chemical and

chironomid records of the impacted lake. The recent changes in chironomids and diatoms suggest eutrophication and deterioration in benthic conditions likely caused by drainage ditch network maintenance activities in the catchments.

Keywords Peat extraction · Aquatic effects · Sedimentation · Chironomids · Diatoms

Introduction

The Finnish Ministry of the Environment (2007) lists peat extraction and forestry as the main stressors affecting the quality of especially the headwaters in Finland. A total of 78% of Finland surface area is in forestry use (22.1 M ha), of which 4.8 M ha is on peatland that has been drained for forestry. Approximately 0.06 M ha of peatlands are in active peat extraction use with additional 0.04 M ha that are no longer in production. Peat extraction activities and the related drainage of the peatlands are known to result in an increase in water flow from the peat production sites, stronger peakedness of the hydrograph, and in the export of suspended solids and dissolved organic matter (see e.g., the review by Kondelin 2006). The leaching of organic matter often induces changes in effluent water color, pH, and metal concentrations. In general, increases in export of phosphorus from peat extraction sites are at the same level with peatlands drained for forestry, whereas nitrogen leaching is higher from peat extraction sites compared to forestry sites (Klöver 2001).

In the receiving lakes, peatland forest drainage or waters from peat extraction sites could induce shifts in lake water nutrient composition, increased color and DOC concentrations, increases in both inorganic and organic suspended

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solids, deteriorating hypolimnetic and top sediment oxygen conditions, increasing internal loading of phosphorus and metals from the poorly oxygenated sediments, and increased sedimentation of organic-rich solids both in the accumulation and transportation zones of the basins (e.g., Kondelin 2006). These physical and chemical changes in the lake water and in the sediment substrate could in turn affect most types of aquatic life and food webs in the receiving water bodies (e.g., Simola 1983; Laine et al. 1995; Laine 2001; Räsänen et al. 2016; Solomon et al. 2016). Kreutzweiser et al. (2013) estimate that while peat extraction is not a significant risk to aquatic biodiversity across boreal Canada, it has a potential for local adverse biological effects.

Despite the well-established effects of peat extraction on water quality and ecology of the receiving surface waters, its unique effects on top of the impacts of ubiquitous forest management are less well known and difficult to study (e.g., Simola et al. 1988). This stems from the similar composition of the loading and from the site specificity of the impacts. The latter is dependent on factors such as the relative extent of peat extraction activities within the watershed, properties of individual peat harvesting sites, and the characteristics and history of the impacted water bodies. Some differences in the composition of loading from peatland forestry and peat extraction may arise due to peat extraction sites having thicker peat layers than forestry sites, deeper (older) layers of peat being exposed during peat extraction, and fertilizers not being used at peat harvesting sites.

Lake Martinjärvi in Keuruu, Central Finland, has been in the center of a public debate over the aquatic effects of peat extraction in recent years. Local residents and summer home owners have suggested that peat harvesting in its watershed has caused deterioration in lake water quality and deposition of several meters thick organic sediment layers. This has proved difficult to verify based on water quality monitoring data alone, because the region as a whole is also heavily drained for forestry. However, paleolimnological methods are known to be powerful tools for the study of aquatic carbon cycling (McGowan et al. 2015). Sediment records also can provide time series of carbon accumulation and watershed erosion (as changes in sediment composition) from the pre-disturbance period, while paleoecological proxies provide information of the responses of biota to disturbance. In addition, a reference lake approach may allow separation of a regional pattern of changes from local point source impacts. We therefore chose to conduct a pairwise temporal sediment study of this impacted lake and a nearby reference lake without a history of peat extraction in its watershed to separate the effects of peat extraction from other local and regional stressors.

In the reference lake setup, peat extraction is expected to cause differences between the lakes that did not exist before. Peat extraction may result in higher accumulation and proportion of organic matter in the impacted lake, a transient phase of mineral-rich sediment at the start of peat extraction, and transient or permanent changes in biological proxies not seen in the reference lake. The changes in biological proxies would likely suggest increased humic content in lake water or deposition of organic matter on the lake bottom.

In addition to attempting to separate the effects of peat extraction from the regional pattern of stressors, the detailed aims of the study were (1) to study the regional (reference lake) and local (impacted lake) histories of stressors affecting the lakes using historical and sediment chemical records, (2) to compare the recent rates of carbon accumulation at the main coring sites of the lakes with the corresponding background accumulation rates, and (3) to investigate the histories of ecological change based on phytoplankton and periphyton (sedimentary diatom remains), as well as zoobenthos (sedimentary remains of chironomid larvae) in the lakes. These paleobiological indicators not only record shifts in species assemblages but also environmental changes in the lakes and their profundal.

Materials and methods

Lake and watershed properties

The study lakes are situated within the boreal forest zone of Central Finland. Peatlands cover about 39% of the catchment areas of both lakes. Besides peat, surficial deposits mainly consist of glacial till derived from Precambrian crystalline rock material. Small glaciofluvial eskers also occur in the area. In 2006, 93% of peatlands in Lake Iso-Kivijärvi catchment were classified as being in forestry use, mainly growing Scots pine. The percentage was 81% for Lake Martinjärvi with an additional 11% of peatlands in peat extraction use. In total, 4% of Lake Martinjärvi catchment area has been drained and cleared of vegetation for peat extraction, half of which was in use in 2010.

General characteristics of the lakes used in the comparison are given in Table 1. Both lakes are shallow and their water qualities are fairly similar, but the larger watershed of Lake Martinjärvi brings about certain differences. Most notably, the residence time of Lake Martinjärvi waters is much shorter than that for Lake Iso-Kivijärvi. This is mainly due to the large watershed rather than the small volume of the basin. There also are several lakes upstream of Lake Martinjärvi that provide basins for

Table 1 Selected properties of the lakes and their watersheds (from public databases)

	Iso Kivijärvi (reference)	Martinjärvi (peat extraction impacted)
Surface area (ha)	190	105
Mean depth (m) ^a	1.6	1.0
Maximum depth (m)	4.5	2.0
Volume (Mm ³) ^a	3.08	1.08
Catchment (km ²)	38	178
Residence time (d)	90	7
Mean thickness of gyttja (m) ^a	1.99	1.37
TOT P (µg/l)	29	30
TOT N (µg/l)	720	651
pH	5.8	6.0
Alkalinity (mmol/l)	0.07	0.05
Conductivity (mS/ m)	3.2	3.0
Color (mg Pt/l)	207	182
Iron (µg/l)	1338	1287

Water quality data are means of 80 (Iso Kivijärvi) and 62 (Martinjärvi) sampling occasions

^a Based on echo soundings in this study

sediment accumulation before the waters reach Lake Martinjärvi.

Forestry practices in the area include drainage ditching, fertilization, harvesting mainly by clear cutting, replanting after harvesting, and management of the growing forests by selectively removing trees. Figure 1 shows the dense drainage network in the watersheds.

Sediment sounding, coring, and dating

The study lakes were surveyed with a sediment penetrating (24 kHz) echo sounder to produce 3D information on the spatial distribution and amounts of soft sediments in the basins. The sounding equipment was based on the MeriData MD 500 echo sounder and MDSC data collection software. The results were processed and sediment unit boundaries were identified with the MDPS software and the sediment units were visualized with Golden Software Surfer 12.

The deepest parts of the lakes were cored in March 2012 (Fig. 1). The main coring site of each lake was cored with a Kullenberg-type piston corer to penetrate the whole pack of lacustrine sediments for determination of long-term carbon and sediment accumulation rates. In addition, the top sediment was cored with a large-diameter (146 mm inner diameter)-cable-operated piston sampler to provide enough sediment material for all biological, chemical, and physical determinations without the need to correlate several cores.

Several additional locations from both lakes were further cored with a Limnos gravity corer for short cores used for Cs-137 dating. These cores provide information of sediment focusing and, in this respect, the representativeness of the main coring site. The Limnos and large dimension cores were sliced in 1-cm slices in the field while the long piston cores were transported to the laboratory in their plastic tubes.

The cores were dated with the Cs-137 (all cores), Pb-210 (large-diameter piston cores), and C-14 (long cores) methods. Cs-137 measurements were made by the Geological Survey of Finland (GTK, all cores) and by the Finnish Nuclear and Radiation Safety Authority (STUK; large-diameter cores) in conjunction with the Pb-210 dating. The constant rate of supply (CRS) model was used for Pb-210 age modeling (Appleby and Oldfield 1978). CRS models are suitable for sites which have experienced rapid acceleration in accumulation in recent times (Appleby and Oldfield 1978). The C-14 datings were made on bulk sediment samples with the acid–alkali–acid treatment (e.g., de Vries and Barendsen 1954) followed by accelerator mass spectrometry determinations at the Helsinki University AMS facility (Tikkanen et al. 2004). The results were transformed to calendar years (BP) using the IntCal 13 correction curve (Reimer et al. 2013) and the OxCal 4.2 software (Bronk-Ramsey 2009).

Chemical and physical analyses

The large-diameter master cores were analyzed for sediment chemical composition to obtain information on past land use changes and other stressors that may have affected the lakes. Samples were freeze-dried for geochemical analyses with ICP-MS and ICP-AES from microwave-assisted HNO₃ leachates (Method 3051a; US EPA 2007). The digestion breaks down sulfides, most salts (e.g., apatite), carbonates, trioctahedral micas, 2:1 and 1:1 clay minerals, but does not appreciably dissolve major silicates. Potassium from micas and clay minerals is, therefore, a better indicator of mineral erosion than Al when this digestion is used. A CN analyzer was used to determine carbon and nitrogen concentrations. All analyses were performed in the accredited testing laboratory of Labtium Ltd (FINAS T025). Internal standards and duplicate analyses were used for quality control. In addition, magnetic susceptibility measurements were made from the main cores with a Bartington MS21 susceptibility meter to obtain additional information on the relative abundance of mineral matter in the sediment.

Separate subsamples from the large-diameter cores (for shallower sediments) and the long cores (for deeper sediments) were weighed and dried to determine sediment dry matter contents. This information was used together with

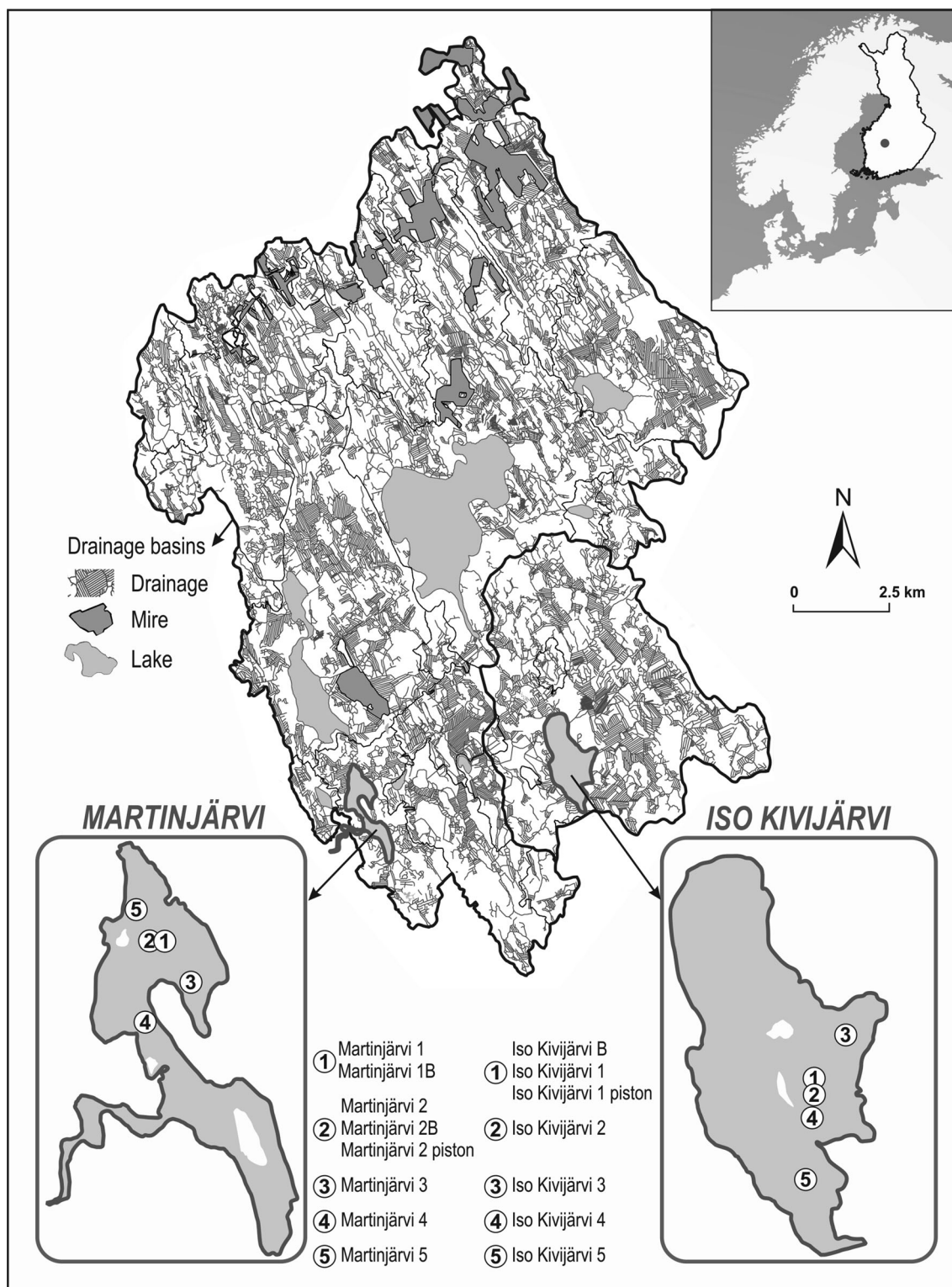


Fig. 1 Map of the study lakes and their watersheds showing the intensity of drainage ditching and peat extraction in the area. Coring sites are shown in the blowups of the study lakes

carbon concentrations, sediment bulk density, thickness (height) of the sediment section, and dating results to estimate (apparent) carbon and dry matter accumulation

rates ($\text{g/m}^2/\text{a}$) for three periods: recent sediments (post-1986; peat extraction impacted), recent background ($\sim 1820\text{--}1900$ AD; lower end of Pb-210 dating), and long-

term background (~ 3000 – 7500 BP; between the C-14 dating samples of each lake). Since most of the organic carbon accumulation happens during the first few decades after deposition on the lake floor and continues at a slower pace deeper in the sediment (e.g., Gälman et al. 2008; Ferland et al. 2014), the top sediment accumulation rates always appear to be higher than in the older sediment sections. However, these apparent increases in carbon accumulation can be compared between the lakes assuming the decomposition rates are roughly similar in both lakes. This approach should allow detection of whether major increases in carbon accumulation have occurred in the peat extraction-impacted lake, but interpretation of subtle changes requires caution.

Chironomid analyses

Chironomid remains were studied to infer past changes in lake trophic levels and sediment chironomid assemblages (e.g., Itkonen et al. 1999; Luoto 2010). A total of 21 levels were analyzed from both lakes: 1–16 cm (1 cm resolution), 18, 20, 24, and 36 cm. Subsamples of 1.5–10 g were deflocculated in 10% KOH solution at room temperature for about 16 h and rinsed on a 100- μ m sieve. All chironomid headcapsules and phantom midge mandibles were picked out from a grooved disk using a stereo microscope at 25–50 times magnification and mounted in Euparal[®] on glass slides for identification. The midge remains were mainly identified according to Wiederholm (1983) and Brooks et al. (2007), but the keys by Hofmann (1971), Saether (1975), and Nilsson (1997) were also used. The information about the ecology of the chironomid larvae used in this study was mainly from publications of Saether (1979), Wiederholm (1983), and Brooks et al. (2007).

Diatom analyses

Diatom remains were analyzed to record a history of algal species assemblages in the lakes. Diatom slides were prepared according to standard methods (Battarbee et al. 2001), and the slides were studied with a light microscope at 1000 \times final magnification. A total of 21 levels were analyzed from the same depths as chironomid remains. A minimum of 300 valves were identified from each slide where possible, but in some samples only 200 valves were found. The Krammer and Lange-Bertalot book series was used as the main reference for identifications (Krammer and Lange-Bertalot 1986, 1988, 1991a, b).

Numerical methods

Profundal Invertebrate Community Metrics (PICM) (Jyväsjärvi et al. 2014) was calculated for each chironomid

subsample to assess the past changes in lake trophic levels (scale: 0–5). Low PICM values indicate eutrophy and high values oligotrophy. PICM takes into account occurrence of 46 species and is a more reliable index for shallow waters than the Benthic Quality Index (BQI) (Wiederholm 1980), as the seven species included in BQI are often missing from shallow lakes even if they are in natural state (Aroviita et al. 2012; Jyväsjärvi et al. 2014). Taxon richness was calculated for each subsample to explore the possible changes in number of chironomid taxa. The effect of subsample size on taxon richness of chironomids was eliminated by rarefaction with 1000 permutations created with an Excel macro. The Past software (Hammer et al. 2001) was used for rarefaction of the diatom results.

Past lake water total phosphorus concentrations (diatom-inferred TP: DI-TP) were modeled from the diatom identification results using a two-component weighted averaging partial least squares diatom-TP transfer function with leave-one-out cross-validation (Tammelin and Kauppila 2015). The transfer function was particularly developed for shallow, humic, and eutrophic lakes. Its training set (50 sampling sites) covers a TP concentration gradient between 7 and 122 μ g P/l. To validate the DI-TP results, we compared them to monitoring data available for the study lakes. Furthermore, we calculated the percentage of diatom taxa in Lake Martinjärvi and Lake Iso Kivijärvi samples that were included in the transfer function.

A before-after-control-impact-type analysis was conducted to study whether the difference between the reference and impacted lakes changed in the peat extraction period. Sediment samples were matched based on the dating results by pairing samples with corresponding ages and leaving out samples that had no matching samples in the other core. The matched data set contained 17 sample pairs down to AD 1830. Iso Kivijärvi-Martinjärvi differences were calculated for the C/N ratio, DM and C accumulation rates, and concentrations of K, C, and N for each sample pair. Two-tailed two sample *t* tests were then used to test if the post-impact alterations were significant. The \sim AD 1830–1980 period (i.e., the deeper part of the Pb-210 dated section) was used as the reference period for the geochemical proxies. The two reference periods for the DM and C accumulation rates were described above.

Historical records on stressors

Table 2 presents a generalized history of land use in the study region. Information on permanent housing and summer cottages was obtained from the City of Keuruu. Agriculture was estimated to have started at the same time with first habitation. The earliest information on forestry was available from the early twentieth century (Vilhola

Table 2 Timing of major external stressors in the study area

Year	External stressor/event
Early 1870s	Commercial loggings begin in Keuruu
1885–1890	First permanent settlements and agricultural fields in Lake Martinjärvi watershed
1920	First permanent settlements by Lake Suojärvi (immediately upstream from Lake Martinjärvi)
1920	First permanent settlements in Lake Iso Kivijärvi watershed
Late 1920s	Old growth forests largely logged
1929	Land owners advised to drain their forests for better growth
1960s	Agricultural fields more widespread than at present
1960	First preparations for a peat extraction area begin in the upper part of Lake Martinjärvi watershed
1960s–1970s	Intensive drainage ditching in the watershed
1960s–1970s	<i>K</i> and <i>P</i> fertilization of peatlands for forestry common in Finland
1970s–1980s	Clear-cut loggings of most forests on mineral soils in the area
1972–1976	First peat extraction areas start production
1978	Preparations begin at the peat extraction area closest to Lake Martinjärvi (Kalmuneva; 56 ha)
Early 1980s	Forest ditching largely completed
1982	Production begins in Kalmuneva
2000s	Construction of summer houses
2000s	Maintenance (clearing) of old drainage ditches (mainly 2004–2007)

1986). Timing of ditching of the peatlands for forestry was estimated from topographic maps of the National Land Survey (1960, 1983, and 1989) and from Kenttämies and Mattsson (2006). Information on maintenance of forest ditches was obtained from land owners and Suomen Metsäkeskus covering the time period from the 1990s to 2010. This information covered 40% of the forest area within Lake Iso Kivijärvi watershed and 60% from the watershed of Lake Martinjärvi. Information on the history of peat extraction in the Lake Martinjärvi watershed was obtained from published environmental permits of Regional State Administrative Agencies.

Results

Artificial radionuclides

All sediment cores showed a marked peak in Cs-137 activity concentration, regardless of the coring location (Fig. 2). This is typical for Southern Finland, which received heavy fallout from the Chernobyl accident in April 1986. Lake Iso Kivijärvi cores 1, 1 piston, 2, and 3 had clearly defined Cs-137 peaks with a rapidly decreasing downward diffusion tail and also a major decrease after the peak, despite the continuous transport of the radionuclide from the catchment. The peak concentrations were found between 7 and 9 cm in these cores, regardless of their

location in the basin. Peaks in Lake Iso Kivijärvi's southernmost cores, 5 and especially 4, were less well defined, with concentrations peaking at 7 (core 5) and 2 cm (core 4).

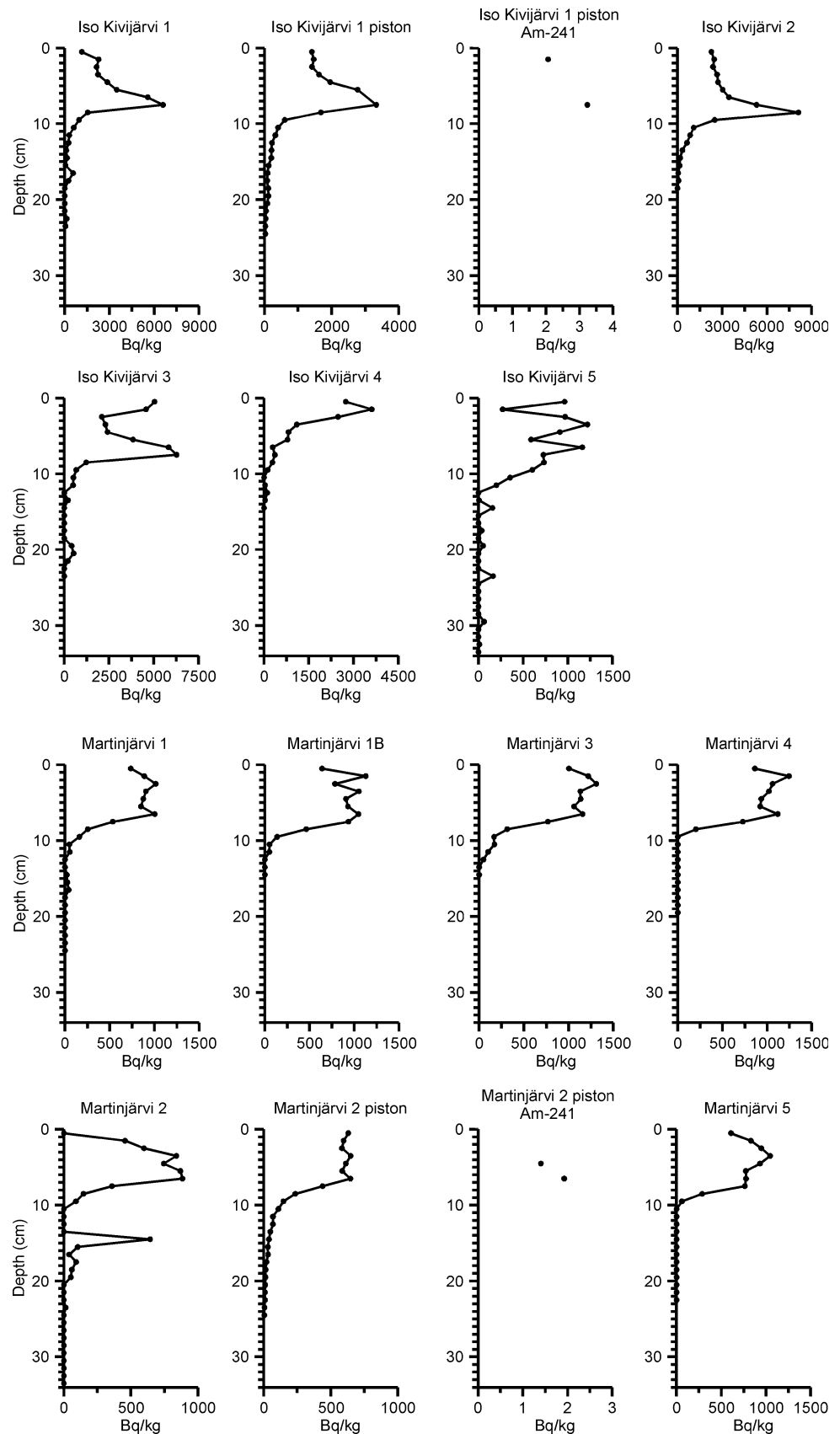
Am-241 is considered less mobile in sediments than Cs-137. Only two samples from the upper part of the Iso Kivijärvi piston core had measurable Am-241 activity concentrations, with the highest measured Am-241 concentration matching the peak in the Cs-137 profile.

Similar to the reference lake, the Cs-137 activities peaked between 7 and 8 cm in the Lake Martinjärvi cores. While the initial increase in Cs-137 was almost as rapid as in the Iso Kivijärvi cores, the post-peak concentrations remained higher in this lake of short residence time and large catchment. The activity concentrations also were markedly lower in Martinjärvi than in the reference lake. Similar to Lake Iso Kivijärvi, the highest measured Am-241 activity concentrations coincided with the peak in Cs-137 in the Martinjärvi 2 piston core.

Natural radionuclides

Figure 3 shows the Pb-210 dating results of the large-diameter piston cores (Iso Kivijärvi 1 and Martinjärvi 2) as an age–depth graph. The upper parts of the graphs with error bars show the Pb-210 CRS dating results (mid-point is the CRS-estimated age and the error bars show the cumulative error related to the measurement and the

Fig. 2 Distribution of Cs-137 and Am-241 in the cores. *Note* the variable scales for the activity concentrations



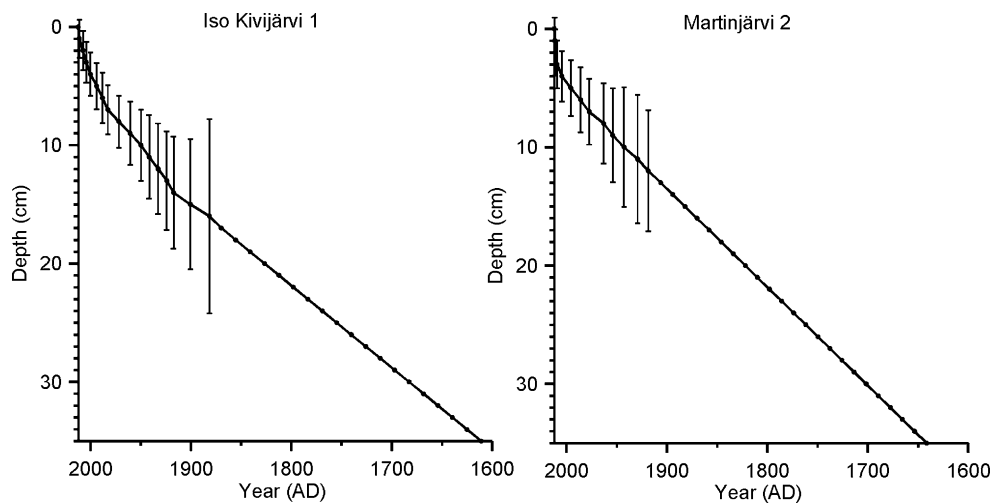


Fig. 3 Pb-210 dating results (with errors) and age–depth models for the main cores (large-diameter piston cores). The *lower parts* of the models are based on simple linear extrapolation

model). The lower part of the age–depth model, below the Pb-210 dated levels, is a simple linear extrapolation of the lower part of the Pb-210 dated section (Fig. 3).

Four levels were C-14 dated from the long piston cores to estimate long-term carbon and dry matter net accumulation rates for sediment sections between the dated samples (Table 3). The results show that sediments at 100 cm depth are several thousands of years old in both lakes and that the deposition of organic-rich gyttja started ~7500 BP in both basins (lowermost C-14 samples).

Carbon and dry matter accumulation

To study whether peat extraction has caused an extra increase in carbon accumulation, the recent carbon accumulation rates were compared to their site-specific background levels in both lakes. There was some variation between the calculated DM and C accumulation rates between the individual C-14 samples with higher background accumulation rates in the impacted lake (long-term

reference; Table 4). Due to the variability, however, the background accumulation rates were not statistically significantly different between the lakes (*t* test). The accumulation rates were higher in Lake Martinjärvi also for the recent reference period (~1820–1900; Table 5). Both the DM and C accumulation rates were higher in the post-1986 sediment section than in either of the reference sections in both lakes (Table 6). In the reference lake, the recent DM accumulation was three times higher than in the past while in Lake Martinjärvi the increase was 2.5× from the long-term reference and 2× from the recent reference. As expected, increases in carbon net accumulation from the long-term background were higher than for DM (5× in the reference lake and 4× in the peat extraction-impacted lake) while the more recent increases corresponded to the increases in DM accumulation: 3× in Iso Kivijärvi and 2× in Martinjärvi. Net accumulation rates in recent sediments were thus somewhat higher in the reference lake than in the peat harvesting-impacted lake when compared to their respective background levels.

Table 3 Radiocarbon dating results for the long cores

Lab code	Site/core	Mid depth (cm)	$\delta^{13}\text{C}$ (‰)	C-14 age (BP)	±
Hela-3391	Iso Kivijärvi 1	100	−30.9	4741	53
Hela-3392	Iso Kivijärvi 1	150	−31.5	6005	63
Hela-3393	Iso Kivijärvi 1	180	−31.8	6284	63
Hela-3394	Iso Kivijärvi 1	220	−31.8	7439	55
Hela-3387	Martinjärvi 2	100	−30.4	3583	69
Hela-3388	Martinjärvi 2	190	−30.4	5033	70
Hela-3389	Martinjärvi 2	275	−31.1	6008	69
Hela-3390	Martinjärvi 2	350	−31.4	7499	57

The laboratory identifier, sample information (core, mid-depth of the 2-cm slice), $\delta^{13}\text{C}$ used for the calculations, and the radiocarbon age with errors

Table 4 Carbon and dry matter accumulation data for the sediment sections between the C-14 samples in Lake Iso Kivijärvi (reference) and Lake Martinjärvi (peat extraction-impacted)

Depth range (cm)	Time span (a)	Average density (g/cm ³)	Average DM (%)	Average C (%)	DM accumulation (g/m ² /a)	C accumulation (g/m ² /a)
<i>Iso Kivijärvi</i>						
100–150 cm	1264	1.113	12.7	12.9	72.7	6.2
150–180 cm	279	1.109	16.5	8.5	192.0	16.7
180–220 cm	1155	1.124	16.1	8.7	69.8	5.3
100–220 cm	2698	1.115	16.7	8.3	82.8	6.9
SD		0.008	2.1	8.3	69.7	6.3
<i>Martinjärvi</i>						
100–190 cm	1450	1.106	17.9	7.5	123	9.3
190–275 cm	975	1.103	17.7	8.2	170	14
275–350 cm	1491	1.137	22.4	7.4	128	9.5
100–350 cm	3916	1.112	18.9	7.7	134	10.3
SD		0.018	2.6	0.4	25.8	2.7

Table 5 Dry matter and carbon accumulation rates and the underlying data for the post-1986 (=impacted) and ~1820–1900 (=recent reference) sediment sections

Lake	Time span (a)	Thickness (cm)	Avg dens. (g/cm ³)	Avg DM (%)	Avg C (%)	DM (g/m ² /a)	C (g/m ² /a)
<i>Post-1986 section (impacted)</i>							
Iso Kivijärvi	28.4	7	1.08	11.6	12.34	334	42
Martinjärvi	25.8	6	1.06	10.0	11.90	492	49
<i>~1820–1900 section (recent reference)</i>							
Iso Kivijärvi	73.9	6	1.08	11.7	12.75	84	11
Martinjärvi	72.2	7	1.10	18.4	9.54	169	16

These sections are based on Pb-210 dating results

Table 6 Changes in apparent DM and C accumulation in the post-1986 section relative to the ~1820–1900 section and the long-term reference section (=between the C-14 samples)

Lake	Δ DM acc. (from 1820 to 1900) (%)	Δ DM acc. (from long term) (%)	Δ C acc. (from 1820 to 1900) (%)	Δ C acc. (from long term) (%)
<i>Relative changes</i>				
Iso Kivijärvi	296	302	291	499
Martinjärvi	191	267	203	388

Sediment properties

Both cores showed a marked increase in the potassium and magnetic susceptibility erosion indicators (e.g., Boyle 2001; Sandgren and Snowball 2001; Figs. 4, 5). Increases in potassium concentrations began in both lakes no sooner than the 1920s. The magnetic susceptibility profiles were somewhat smoother than the rapidly increasing potassium concentrations and may suggest increased erosion starting as early as the late 1800s. The same is true for C and N concentrations, which started to

decline before the major phase of potassium increase in both lakes.

The proportion of carbon in relation to nitrogen (the share of allochthonous, low-N organic matter) increased in the reference lake mainly after the phase of highest potassium inputs. The effect was also detectable but less marked in Lake Martinjärvi. The onset of peat extraction in the Lake Martinjärvi catchment (between 1972 and 1985, the closest production area since 1982) coincides temporally with a small transient decrease in potassium concentrations in the Lake Martinjärvi sediments, while other

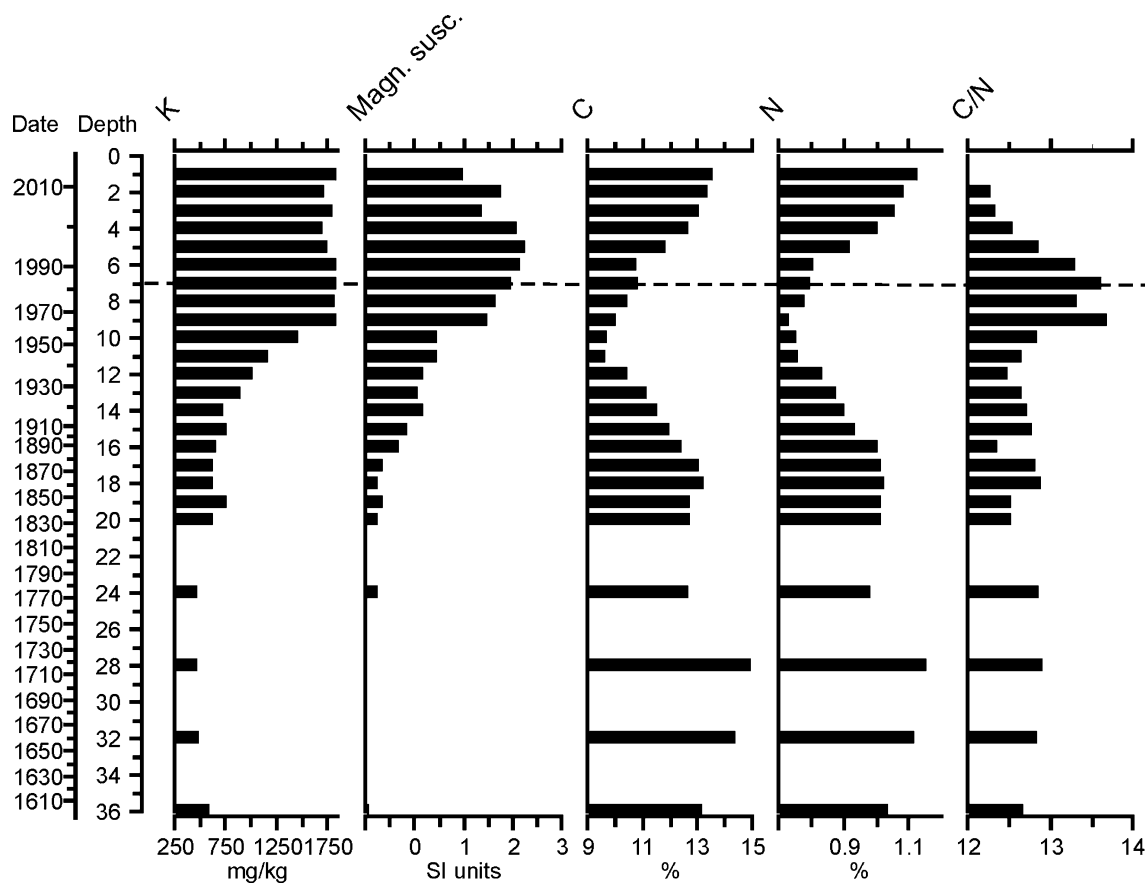


Fig. 4 Distribution of selected sediment properties in the Iso Kivijärvi large-diameter core. Dashed line shows the start of peat extraction at Kalmuneva

sediment properties showed similar, smooth trends in both lakes over that time period. In BACI analysis, the peat mining-impacted period deviated from the reference period for *K* ($p = 0.037$) but not for *C*, *N*, or *C/N* ($p = 0.487$, $p = 0.642$, $p = 0.747$).

Chironomids

The PICM index and stratigraphies of the most abundant taxa with the highest indicator value show that the changes in chironomid communities were greater in the reference lake (Fig. 6) than in Lake Martinjärvi (Fig. 7). Taxa typical of eutrophic shallow lakes were more abundant than taxa of shallow oligotrophic lakes throughout the studied time period in both Lake Iso Kivijärvi and Martinjärvi.

In Lake Iso Kivijärvi, the first clear signs of changes in assemblages date to the 1960s–1970s when the PICM index declined from an average of 2.0 to ~ 1.6 , indicating slight eutrophication (Fig. 6). The most marked change in the chironomid community of Lake Iso Kivijärvi was the decrease of *Heterotanytarsus apicalis*, typical of mineral-

rich environments, starting from the 1960s (Fig. 6). In contrast, *Cladopelma*, a genus typical of eutrophic waters, appeared in the record in the 1970s. Other taxa typical of oligotrophic environments, such as *Heterotrissocladius grimshawi*, *Heterotrissocladius marcidus* and *Stempellina*, occurred sporadically from the seventeenth century to the 1950s–1970s.

There were also certain changes in chironomids in the 1990s–early 2000s in Lake Iso Kivijärvi. *Zalutschia zalutschicola* which is typical of oligotrophic and dystrophic lakes became highly abundant since the 1990s while *H. apicalis* disappeared (Fig. 6). The lowest PICM value (1.3) was observed around AD 2000 and taxon richness decreased markedly from 2000 to 2003.

In Lake Martinjärvi, the PICM value was on average 2.2 before the 1960s (Fig. 7). Lake Martinjärvi has shown slightly more eutrophic (low) values since the end of the 1970s with some fluctuations between 1970 and 2000. The lowest PICM values (1.7) were recorded at the end of the 1970s. Similarly, the proportion of taxa typical of oligotrophy, e.g., *H. apicalis*, *H. grimshawi*, and *H. marcidus* decreased since the 1970s, whereas *Cladopelma* which is

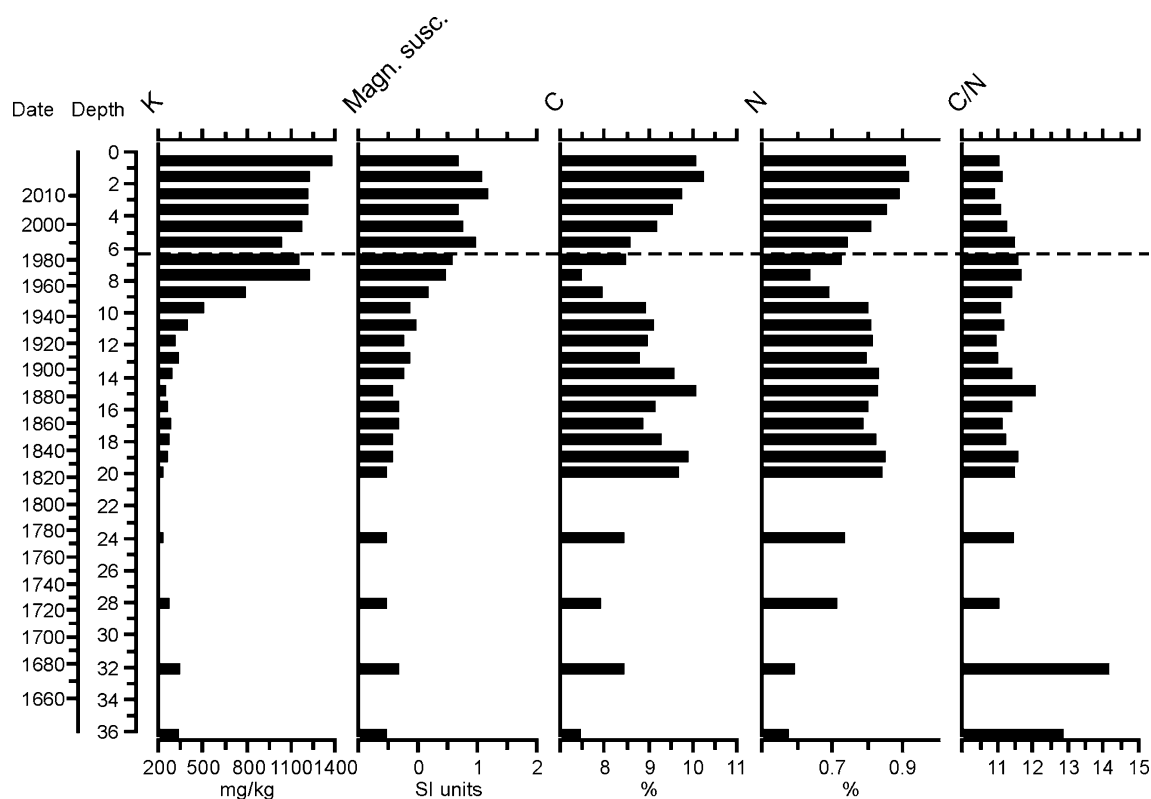


Fig. 5 Distribution of selected sediment properties in the Martinjärvi large-diameter core. Dashed line shows the start of peat extraction at Kalmuneva

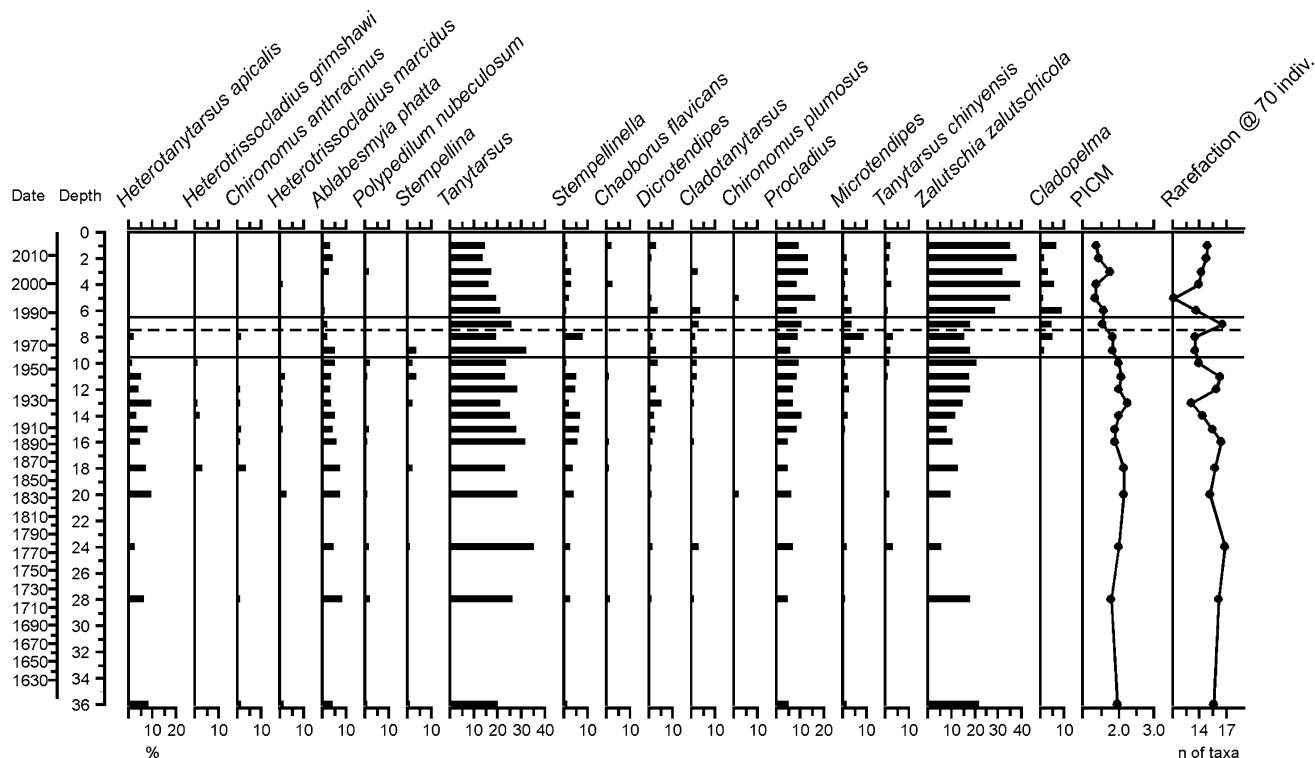


Fig. 6 Distribution of selected chironomid taxa, PICM index values, and rarefaction-estimated numbers of taxa in the Lake Iso Kivijärvi core. Solid lines delineate local assemblage zones discussed in the text. Dashed line shows the start of peat extraction at Kalmuneva

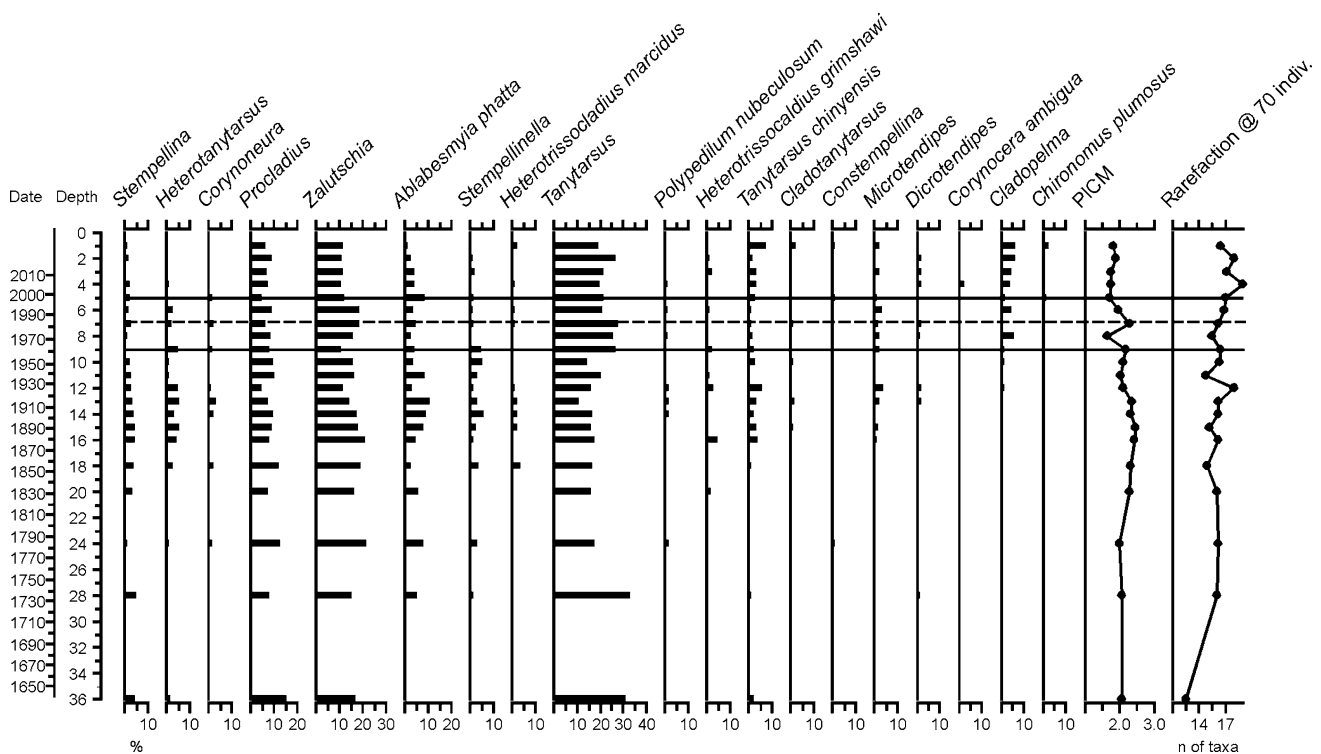


Fig. 7 Distribution of selected chironomid taxa, PICM index values, and rarefaction-estimated numbers of taxa in the Lake Martinjärvi core. Solid lines delineate local assemblage zones discussed in the text. Dashed line shows the start of peat extraction at Kalmuneva

typical of eutrophic environments has become more abundant since the 1970s. There was a clear but transient decrease in the proportion of species typical of oligotrophic conditions from late 1970s to early 1980s in Lake Martinjärvi, when the proportion of eutrophic environment species increased. A similar change in the community was observed in the early 2000s. There was a slightly increasing trend in diversity in Lake Martinjärvi and the taxon richness was at the highest around 2010 (Fig. 7).

Diatoms

The Lake Iso Kivijärvi diatom record showed three major changes in assemblage composition: a profound but gradual change starting at the end of the 1800s, and marked shifts in the early 1960s and late 1990s–early 2000s (Fig. 8). The first change, which coincides with the onset of agriculture and logging in the area, was characterized by increases in eutrophic species such as *Tabellaria fenestrata* and *Aulacoseira ambigua*, as well as certain *Eunotia*, *Anomoeoneis*, and *Neidium* species. The share of planktonic taxa started to increase gradually and the number of taxa declined. The next shift at ~9 cm in sediment (1960s) involved declines in species such as *Aulacoseira alpigena*, which prefers oligotrophic conditions, the mesotrophic *Aulacoseira lirata*, and some oligotrophic *Anomoeoneis*

and *Eunotia* species. In contrast, the relative abundances of *T. fenestrata*, mesotrophic taxa such as *Aulacoseira distans* (+var. *nivalis*) and *Asterionella formosa* as well as the oligo-dystrophic *Eunotia sudetica* increased. The most recent change in the reference lake dates to 1990s–early 2000s and was characterized by a marked decline in *T. fenestrata* and increases in the mesotrophic *A. subarctica* and *A. distans*. *A. ambigua* recovered from a temporary decline and *A. distans* var. *tenella* appeared in the diatom record.

The diatom record of the peat extraction-impacted Lake Martinjärvi showed the same general shifts in species composition as the reference lake (Fig. 9). In contrast to the reference lake, the first major change in the diatom stratigraphy of Lake Martinjärvi was characterized by an abrupt increase in the mesotrophic *A. lirata*. The shift also occurred before the onset of permanent agriculture or logging in the area. The gradual increase in planktonic diatoms was missing in Lake Martinjärvi. The next shift in assemblages in the 1970s roughly corresponds in timing to a similar shift in the reference lake and the onset of modern drainage ditching in the region. The relative abundances of *A. lirata* and a number of *Eunotia* and *Neidium* species declined, while the abundances of species such as *T. fenestrata*, *T. flocculosa*, *Aulacoseira perglabra*, *A. distans* var. *nivalis*, *E. sudetica*, and *Cymbella gracilis* increased. The most recent change in the 2000s was of similar type

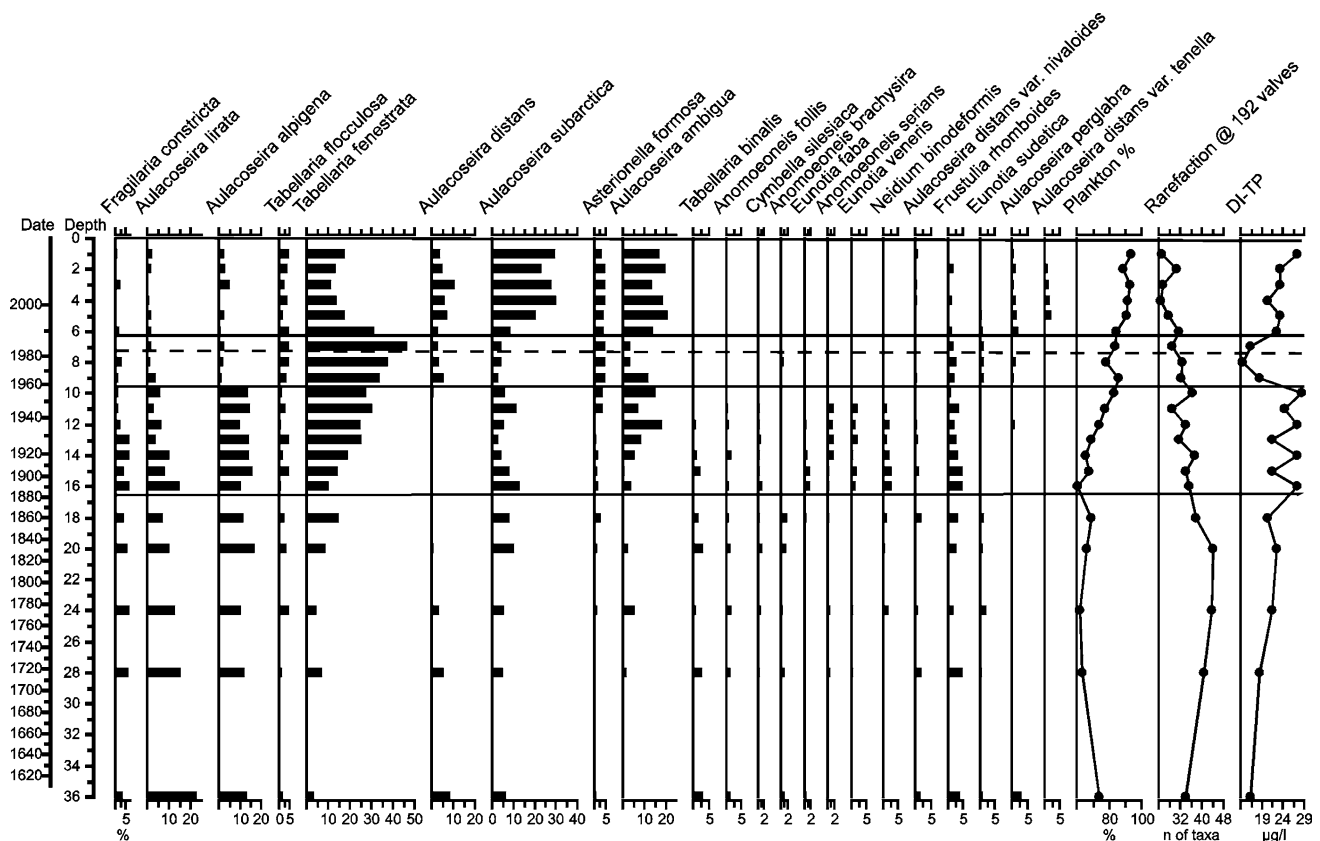


Fig. 8 Distribution of selected diatom taxa, plankton percentage, rarefaction-estimated numbers of taxa, and DI-TP in the Lake Iso Kivijärvi core. *Solid lines* delineate local assemblage zones discussed in the text. *Dashed line* shows the start of peat extraction at Kalmuneva

than in the reference lake. The most abundant species (here *A. lirata*) declined, while *A. subarctica*, *A. distans*, *A. ambigua*, and even the very eutrophic *A. granulata* increased. Low numbers of taxa were recorded in the early 2010s.

The onset of peat production falls between the shifts in diatoms in the early 1970s and 2000s. The 7–8-cm sample dates approximately to the early 1970s, when the first peat harvesting areas in the upper reaches of Lake Martinjärvi watershed started production, and differs from the adjacent samples with less *A. lirata* and small peaks in certain small *Navicula* taxa, but there are also similar short declines in *A. lirata* elsewhere in the stratigraphy.

Altogether, 60–91% of taxa identified from the Lake Iso Kivijärvi and Lake Martinjärvi samples were found in the calibration set used for lake water TP reconstructions. The model predicted measured TP concentrations correctly for the most recent period (2004–2012), but underestimated the highest individual observations from both lakes and the oldest concentrations in Lake Iso Kivijärvi. The trends in the diatom-inferred TP concentrations were similar in both lakes: increases since the late eighteenth century, elevated values until the 1960s, a decrease in the 1970s and 1980s,

and a new increase in the 1990s. Since the 2000s, the DI-TP has steadily increased in Lake Iso-Kivijärvi but remained stable in Lake Martinjärvi. DI-TP indicates that the lakes have become more eutrophic during the last 400 years, and the peat production-impacted Lake Martinjärvi less so than the reference lake.

Discussion

Sediment distribution and recent sediment accumulation

In contrast to what has been suggested in public debate, peat extraction has not resulted in the deposition of thicker lacustrine sediment beds in Lake Martinjärvi when compared to the reference lake. In fact, both the average and maximum thickness of gyttja were somewhat higher in the reference lake. This is partly explained by the topography of the basins, as Lake Iso Kivijärvi has a number of deep sheltered basins that allow continuous and effective sedimentation. However, the comparable sediment accumulation rates at all coring locations in both lakes suggest a low

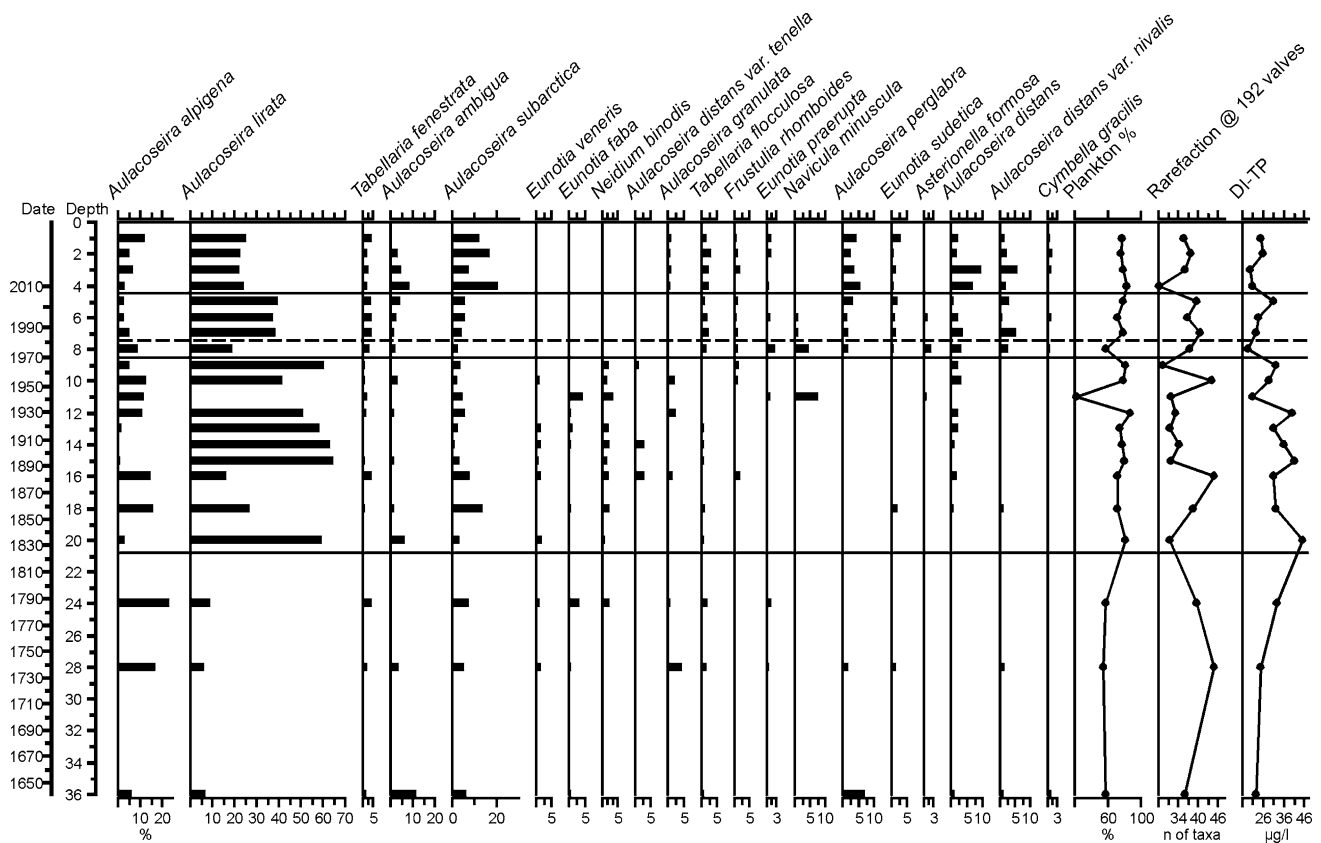


Fig. 9 Distribution of selected diatom taxa, plankton percentage, rarefaction-estimated numbers of taxa, and DI-TP in the Lake Martinjärvi core. Horizontal lines delineate local assemblage zones discussed in the text. Dashed line shows the start of peat extraction at Kalmuneva

level of sediment focusing to the main coring sites at present. In both lakes, echo sounding showed that lacustrine gyttjas extended close to the shoreline in all parts of the lakes. While sedimentation can be poor in very shallow lakes due to resuspension (Niemistö et al. 2008), Lake Martinjärvi still provides favorable conditions for sedimentation, as shown by the constant recent sediment accumulation rates within the basin. Wave base calculations (Håkanson et al. 2004) also suggest that wind stress should still allow sediment accumulation in Lake Martinjärvi despite its current shallowness.

The short residence time and the many upstream lake basins also may partly affect the current sediment accumulation rate in Lake Martinjärvi. The short residence time means higher kinetic energy in the water resulting in less time for particles to settle and for dissolved organic species to coagulate. For instance, in their 305-lake meta-analysis of published phosphorus input/output figures, Brett and Benjamin (2008) found that lake hydraulic retention time was the best predictor of phosphorus loss. Indeed, it is a common variable in phosphorus retention models, including the well-known Vollenweider *P* model (see Brett and Benjamin 2008). In addition, the upstream lakes act as sedimentation basins for particulate matter from the upper

reaches of the large watershed, reducing the loading to Lake Martinjärvi. None of the peat extraction sites drain directly to Lake Martinjärvi.

Carbon accumulation

As discussed above, sedimentation dynamics could explain why sediment layers in Lake Martinjärvi are not thicker than in the unimpacted reference lake. The recent relative increase in carbon and dry matter accumulation was also higher in the reference lake than in the peat extraction impacted lake. However, these deviations between the impacted and reference lakes were not significant in the BACI-type analysis, regardless of the reference period used [DM: $p = 0.600$ (long-term reference), $p = 0.929$ (recent reference); C: $p = 0.786$ (long-term reference), $p = 0.560$ (recent reference)]. The increases (2–3×) were markedly smaller than those reported for DM in the clayey catchments of SW Finland (Mäkinen et al. 2012). The increases in C accumulation in the study lakes were somewhat higher than the doubling of accumulation that was reported for the whole of Europe by Kastowski et al. (2011). Accumulation rates were already fairly high in Lake Martinjärvi during both reference periods when compared with the reference

lake, or even the SW Finnish data set of 22 small head-water lakes (Mäkinen et al. 2012), likely owing to its landscape position and large watershed.

This type of a comparison between coring sites is obviously not detailed enough to estimate the exact contribution of peat extraction inputs to sedimentation in Lake Martinjärvi, but it eliminates the influence of differences in sedimentation efficiency between the lakes. It is unlikely that the sedimentation efficiency of the coring sites (i.e., the proportion of the C and DM inputs to the lake that are deposited at the coring site) has changed markedly from the AD 1820 to 1900 reference period because the depth of the site has changed only a few centimeters from that time.

There is no measured data on carbon and dry matter inputs to Lake Martinjärvi. It appears that either the additional inputs from peat extraction are too small to cause a major increase or the inputs are deposited before they reach Lake Martinjärvi. The first reason most likely plays at least some role because only 2% of the Martinjärvi watershed was in active peat extraction use in 2010. A major contribution of carbon from peat harvesting would thus require a drastic increase in inputs from the peat mining areas (e.g., a doubling of inputs from the whole catchment would require a 51-fold increase in inputs from the active peat extraction areas if transport from the other 98% remained constant). If a major part of the exports from peat harvesting are in dissolved form and if the dissolved species persist in the receiving surface waters, sedimentation also will not increase. However, the water color is not higher in Lake Martinjärvi than in Lake Iso Kivijärvi (Table 1).

Early signs of land use impacts

The sediment properties related to mineral matter inputs (*K* and magnetic susceptibility) show a regional pattern with increasing land use. While increases in *K* began in the 1920s at the latest, magnetic susceptibility began increasing in the late 1800s. The pattern is similar in both lakes, testifying to the regional nature of these impacts. The earliest changes coincide with the onset of logging in the Keuruu region and the intensification phase may be related to the start of agriculture and also drainage of forests (Table 2).

In accordance with physical and chemical changes in the sediment cores, the first signs of human disturbance in the diatom records and DI-TP were seen in the late 1800s in both lakes. These changes corresponded in timing to the first permanent houses in the respective catchments and, presumably, intensified land use for agriculture and forestry. The changes in diatom assemblages were more distinct in the reference lake and obscured to some degree by the short-term fluctuations in Lake Martinjärvi. Corresponding changes were not seen in the chironomid record,

apart from maybe a slight increase in *Z. zalutschicola* in the reference lake. Overall, the changes in diatom assemblages point to the effects of nutrients and humus or pH with increasing proportions of not only planktonic taxa but also *Eunotia*, *Anomoeoneis*, and *Neidium* species. This is in accordance with the findings of, e.g., Manninen (1998) who studied stream algae in a 2-year experiment after forest ditching. The DI-TP record suggests that the trophic status of the lakes likely increased. Early agriculture can cause significant nutrient enrichment even in boreal forest settings (Anderson et al. 1995).

Intensive forest drainage in the 1960s and 1970s

The peak phase of erosion and transport of mineral matter into both lakes was in the 1960s. This was a time of intensive forest drainage, and many of the shallow peatlands were drained during this period as well. The signs of mineral matter erosion partly mask the signal of organic matter inputs to the lakes by diluting the C%, but the high C/N ratio between ~1960 and 1980 may also suggest transport of humus to the lakes (e.g., Kaushal and Binford 1999). This feature was more pronounced in the reference lake, pointing to conditions that allow settling of organic matter at the coring site, but it was also observed in Lake Martinjärvi.

In accordance with physical and chemical changes in the sediment cores, the first clear signs of human disturbance in the chironomid records were seen from the 1960s in Lake Iso Kivijärvi and in the 1970s in Lake Martinjärvi. These changes corresponded in timing to intensified land use for forestry. According to the PICM index, conditions in the lake bottom became less favorable for taxa of oligotrophic environments in both lakes after the 1970s.

The chironomid record suggests increased extent of organic-rich lake bottom and eutrophication of both study lakes since the 1970s due to forest drainage. The peat extraction started at the same time in northern parts of Lake Martinjärvi watershed. Since the 1970s, taxa typical to oligotrophic and minerogenic environments, as well as taxa that build a portable case of sand grains (e.g., *H. apicalis*) decreased, suggesting that the change of chironomid communities in both lakes is related to the intensive drainage and fertilizing of peatlands for forestry. The increased proportion of *Cladopelma* larvae also suggests that *Phragmites australis* stands may have become more abundant in both lakes since the 1970s (Luoto 2010).

Similar to chironomids, the most profound changes in the diatom algae were observed in the 1960s in Lake Iso Kivijärvi and in the 1970s, in Lake Martinjärvi. Diatom-based nutrient modeling shows no signs of nutrient enrichment at that time, but this may be due to the confounding effect of organic matter inputs when

predominantly peaty catchments were drained. In fact, DI-TP declined markedly in Lake Iso Kivijärvi at this time, most likely because of the increase in *T. fenestrata* and the corresponding decline in *A. ambigua*. A similar pattern of changes in diatoms was reported from a peatland drainage-affected lake in Eastern Finland, with responses to early land use followed by more intensive changes in the 1970s (Liehu et al. 1986).

The beginning of peat extraction

The start of peat extraction, particularly in the site close to Lake Martinjärvi (AD 1982, dashed line in the stratigraphic figures), did not coincide with any major changes in sediment properties. However, there was a transient decline in potassium concentration that was not observed in the reference lake. The timing of this shift suggests it may be related to peat harvesting in Kalmuneva (dilution with organic matter).

The low PICM value in Lake Martinjärvi from 1977 to 1985 suggests that the preparation phase (clearing of vegetation, drainage) and the first years of peat extraction in the bog closest to Lake Martinjärvi, Kalmuneva, may have increased transport of suspended solids and nutrients to the extent that it caused a temporary change to a community of more eutrophic environment. Otherwise, the effects of peat extraction on Lake Martinjärvi chironomid communities could not be separated from the effects of forestry. Indeed, the effects of peatland drainage are often most marked immediately after the ditching operations (e.g., Prévost et al. 1999).

The effects of peat extraction could not be identified in the Lake Martinjärvi diatom record and, consequently, DI-TP. There were no changes that correspond to the shift in the *K* concentration at 6 cm in sediment or the fluctuating PICM at 8–7 cm. However, the rapidly fluctuating nature of the Lake Martinjärvi diatom record may obscure such transient shifts in the assemblages.

Recent changes

The chironomid communities did not recover in either lake after the most intensive forest drainage period, a feature also observed by Turkia et al. (1998) and Sandman et al. (1990). In fact, another change in assemblages and a decline in PICM index values were observed at 6 cm in Lake Iso Kivijärvi and 5 cm at Lake Martinjärvi. The increase in *Zalutschia zalutschicola* at 6 cm in Lake Iso Kivijärvi points to increased organic matter inputs to the reference lake as the species is typical to dystrophic waters (Saether 1979). The ditch network maintenance in the 2000s and 2010s may partly explain why the lowest PICM values were observed in the most recent part of the

sediment record in Lake Iso Kivijärvi. This means that the effects of forestry on the recent chironomid record cannot be ruled out in Lake Martinjärvi either. Such maintenance and the related supplementary ditching is known to result in as high loading as initial drainage ditching (e.g., Manninen 1998; Joensuu et al. 1999). The only other known stressor falling in this time bracket is the construction of summer homes in the watersheds, but the ditch maintenance activities involve much larger areas and are known to cause changes in water quality (Manninen 1998).

The recent changes in taxonomic richness of chironomids in both lakes can be related to eutrophication. Diversity of the chironomid community has been observed to increase as a result of slight eutrophication and to decrease as the eutrophication gets more severe (Wiederholm 1980). Changes in taxon richness thus suggest higher recent eutrophication of Lake Iso Kivijärvi than Lake Martinjärvi, in line with the DI-TP results.

The differences in the morphometry and hydrology of the lakes may explain the somewhat different responses of chironomid communities to the allochthonous loading of suspended solids and nutrients. Lake Iso Kivijärvi is deeper than Lake Martinjärvi, which is more easily mixed to the bottom by wind. In addition, Lake Martinjärvi has a very short water residence time. Oxygen-consuming organic matter also accumulates as sediment more easily at the Lake Iso Kivijärvi coring site than in the turbulent Lake Martinjärvi.

Similar to chironomids, changes in diatom assemblages were observed also in the most recent sediments (topmost 5–6 cm in Lake Iso Kivijärvi, 4–5 cm in Lake Martinjärvi). This corresponds to the 1990s in Iso Kivijärvi, and late 2000s in Martinjärvi. Drainage network maintenance may thus have contributed to the observed changes in diatoms as well. Interestingly, however, the changes in chironomids appear to occur slightly before the corresponding changes in diatoms in Lake Martinjärvi, suggesting that profundal conditions have deteriorated rapidly in response to the latest stress.

Conclusions

Contrary to the perceptions of many local residents and summer home owners, the results show that peat extraction has not resulted in excessively thick lake sediment deposits at any of the coring locations in the impacted lake when compared to the reference lake. Similarly, no differences were found when the recent increases in carbon accumulation were compared between the peat extraction-impacted and the reference lakes. This is not due to sedimentation dynamics (short residence time and shallowness of the impacted lake) because coring site-specific

reference accumulation rates were used in the calculations. The lack of major impacts on sedimentation results at least partly from the limited extent of peat extraction sites in the catchment. Furthermore, some of the inputs will be lost by sedimentation in the upstream basins before reaching the study lake. Upstream basins are important in managing the downstream effects of sedimentation and the landscape position of the impacted lake has an effect on the results of this study as well. More studies with lakes in different settings are therefore needed before more general conclusions can be made.

The use of sediment records and the pairwise comparison allowed identification of a regional pattern of impacts that is closely related to the history of land use, particularly forestry, in the region. A reference site and adequate dating control reduce the risk of attributing all detected changes to the stressor of primary interest. Modern forestry practices increased the extent of soft, organic-rich bottom zones and eutrophication in the lakes. The approach also allowed identification of possible transient signs of the starting phase of peat extraction in the chemical and chironomid records of the impacted lake. The recent changes in chironomids and diatoms in the 2000s and 2010s point to eutrophication and deterioration in benthic conditions. These ecological changes appear to have been caused mainly by drainage ditch network maintenance activities in the catchments, although other activities may play a role as well (peat extraction, summer homes). The aquatic effects of ditch maintenance clearly warrant further studies.

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